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Volume 15 APRIL, 1945 Number 1

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

« CONTENTS »

Shape Variation of Some Lake Superior Beach Pebbles ..... *Robert M. Grogan* 3

Heavy Black Sands on Some Victorian Beaches ... *George Baker* 11

Unusual Nuclei in Oölites from the Morrow Group Near Fayetteville, Arkansas ..... *Lloyd G. Henbest* 20

Clay-Pellet Conglomerates at Hobart Butte, Lane County, Oregon ..... *Victor T. Allen and Robert L. Nichols* 25

ANNOUNCEMENT

Aerogeology in Mineral Exploration ..... Colorado School of Mines 34

REVIEWS

R. A. Bagnold. The Physics of Blown Sand and Desert Dunes ..... *W. H. Twenhofel* 35

C. S. Piper. Soil and Plant Analysis ..... *W. H. Twenhofel* 35

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The subscription price of the *Journal of Sedimentary Petrology* is $3.00 per year prepaid to addresses in the United States.

Single numbers, $1.50 each.

Postage is charged extra for all other countries: 40 cents on annual subscriptions (total $3.40).

The *Journal* will furnish reprints at cost. Orders should accompany corrected galley proof.

Communications about the *Journal*, subscriptions, rates, memberships, change of address, advertising and non-receipt of preceding numbers should be addressed to Society of Economic Paleontologists and Mineralogists, P.O. Box 979, Tulsa, Oklahoma. Claims for non-receipt of preceding numbers must be sent in within three months of the date of publication in order to be filled gratis.

Communications in regard to manuscripts or purely editorial matters should be addressed to W. H. Twenhofel, Editor, University of Wisconsin, Madison, Wisconsin.

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN, U.S.A.

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NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 15, NO. 1, PP. 3–10
FIGS. 1–7, TABLE 1, APRIL, 1945

SHAPE VARIATION OF SOME LAKE SUPERIOR BEACH PEBBLES

ROBERT M. GROGAN
Urbana, Illinois

ABSTRACT

The measured roundness and sphericity of originally angular rock fragments derived from a rhyolite cliff on Lake Superior show a progressive increase with linear distance of travel as beach pebbles. The general applicability of Krumbein's equation of rounding to the rounding of these pebbles is tested by a graphical method.

INTRODUCTION

A pebble beach on the Minnesota shore of Lake Superior near the mouth of Split Rock River affords an excellent opportunity to study the progressive modification of pebble shape produced by wave action. It was found and examined in the summer of 1938 during field work toward the preparation of a doctorate thesis at the University of Minnesota, and samples collected at that time were studied somewhat later as a basis for this paper.

SOURCE AND NATURE OF SAMPLES

The beach (Fig. 1) is gently curved and extends for slightly less than one-half of a mile in a general N. 15° E. direction. It is terminated at the northeast end by a sheer cliff of rhyolite rising approximately 40 feet above lake level, and on the south by a small jutting headland of basalt. Both rhyolite and basalt are gently dipping lava flows of Middle Keweenawan age.

The beach ranges in width from only a foot or two at the base of the rhyolite cliff at the northeast end to a maximum of about 50 feet near the south end. It is composed dominantly of pebbles although a small quantity of coarse sand is present at most places and a few cobbles are present near the northeast end. Ninety per cent or more of the pebbles are of rhyolite derived from the cliff at the northeast end of the beach. Their origin is attested by their petrographic similarity to the rhyolite of that cliff, by progressive increase in rounding with distance from the cliff, and the fact that no other mass of similar rhyolite crops out along shore for miles in either direction.

The rhyolite is a tough, dense, pinkish- to yellowish-brown porphyry. As seen under the microscope it contains 10 per cent phenocrysts of orthoclase and oligoclase-andesine in a fine-grained groundmass composed of about equal parts orthoclase and quartz. In outcrop the rock is complexly and closely jointed (fig. 2), making it easily attacked by freezing and thawing and by waves. The joint blocks range from less than fist-size to masses a foot or two in maximum dimension. The shapes of most blocks fall into two general categories, one group comprising roughly equi-dimensional, sharp-edged polyhedrons, the other slab-like forms whose two longest axes lie in a plane originally parallel to the vertical face of the cliff.

The strongest and most persistent winds of the region are from the northeast. The beach is fully exposed to their force. Waves and alongshore currents attending the winds coming from that direction sweep accumulated joint blocks from the talus pile beneath the rhyolite cliff southward onto and along the beach. Observations on the effectiveness of wave action lead to the conclusion that only during times of strong or storm winds is there appreciable movement or wear of pebbles the size of those here studied.

Commonly a beach ridge of variable height and width paralleling the shore several feet from the water's edge remains after a period of strong wave action. Twelve samples were taken from such a ridge at intervals of 200 feet for a distance of 2200 feet beginning at its northeastern end (fig. 1). The height of the ridge ranged from 1 to 5 feet above the general beach level and its distance from the water-line ranged from 5 to 15 feet. In collecting the samples care was taken to make them representative of the pebble shapes at that point, to include only pebbles with longer diameters of approximately 25 to 75 mm. for size uniformity, and to include only rhyolite pebbles.

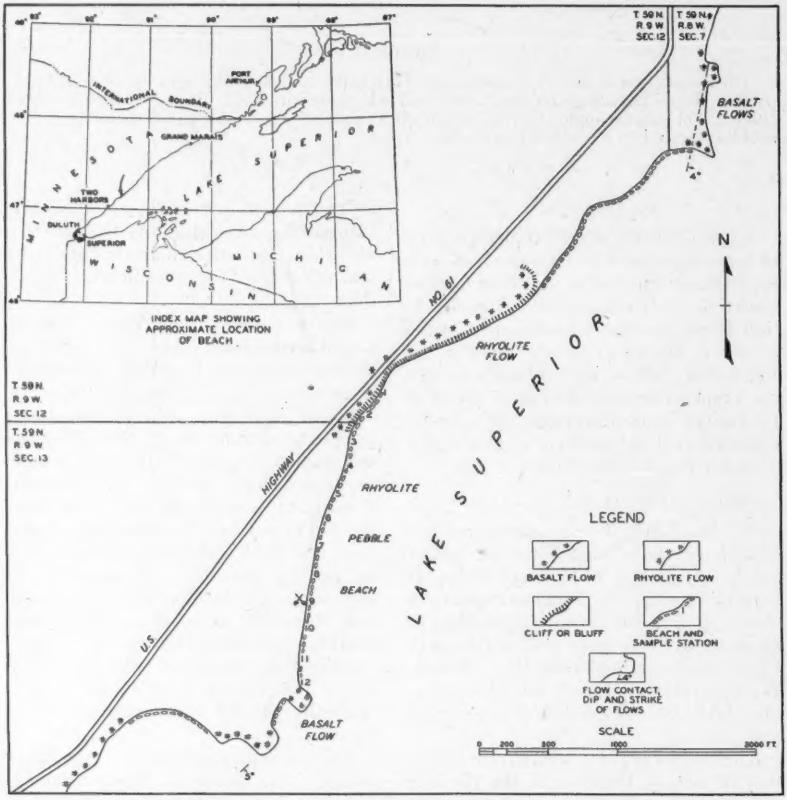

FIG. 1.—Sketch map of part of Minnesota shore of Lake Superior showing location of rhyolite outcrop and rhyolite pebble beach.

VISUAL CHANGE IN PEBBLES

A progressive change in roundness of pebble outline was strikingly apparent in the field. Groups of pebbles from four samples are shown in figure 3. Group 1 represents the sample taken at the northeasternmost end of the beach where frag-

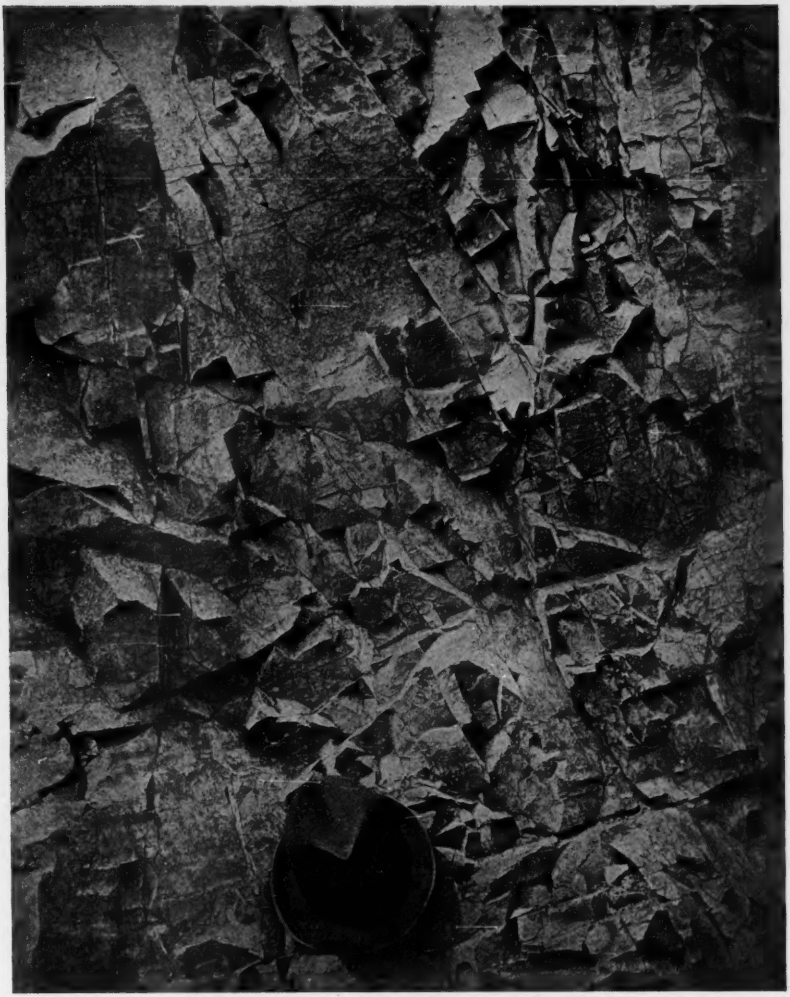

FIG. 2.—Close view of complexly jointed face of the rhyolite flow which is the source of the beach pebbles.

ments of rhyolite were first being subjected to wave action. Groups 2 and 6 are from samples at distances of 200 and 1000 feet, respectively, from group 1, and group 12 is part of the sample taken at the extreme southern end of the beach, at a distance of 2200 feet from the first sample.

The pebbles of group 1 are the most angular, those in groups 2 and 6 show intermediate degrees of rounding, and those in group 12 are most rounded. Group 2 is particularly interesting in that it demonstrates that 200 feet of along-shore travel is, under the prevailing conditions, entirely adequate to round off all the sharp corners and edges present on the originally angular rock fragments. The degree of smoothing of rough and hackly surfaces increases with the rounding of edges and corners, culminating in a fair degree of polish on the pebbles of group 12. The progressive visual change in particle shape (sphericity) is not nearly so marked as in the two other properties. Suggestions of various regular polyhedral shapes, prisms and pyramids, for example, are about as common among the pebbles of group 12 as group 1.

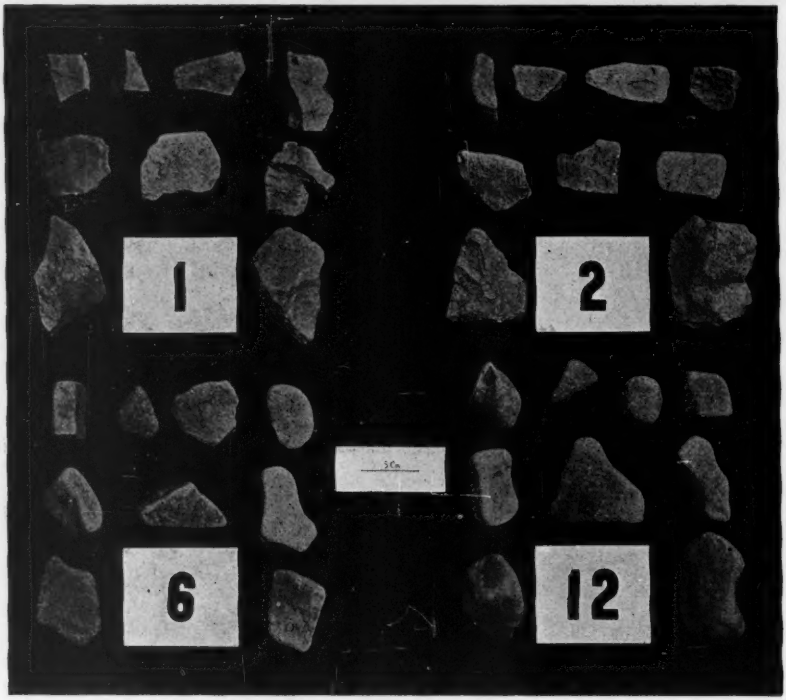

FIG. 3.—Groups of pebbles from samples 1, 2, 6, and 12, demonstrating progressive increase in rounding with distance from source.

NUMERICAL DATA AND INTERPRETATIONS

Numerical expression of the average shape and roundness of each of the samples was obtained by taking the mean of volume sphericity measurements on individual pebbles by the practical method

suggested by Wadell (Wadell, 1934) and the mean of visual roundness measurements on the same pebbles by Krumbein's method (Krumbein, 1941a). The results are given in table 1, together with the linear distance traveled by the pebbles, the number of pebbles included in each sample, and the mean length of the long diameters of the pebbles. The latter figures are included to give some sphericity in the first 600 feet is not known. The initially steep, then more gradually rising trend of the roundness curve is emphasized by the broken line, which represents a moving average of three roundness measurements.

The major irregularity at the 1600-foot ordinate which is present in both curves reflects a disturbance of sedimentation equilibrium in the vicinity of that point.

TABLE 1

Sample No.	Linear distance of travel, feet	Number of pebbles	Mean long diameter, cm.	Mean sphericity	Mean roundness
1	0	22	6.9	.55	.26
2	200	21	7.1	.51	.40
3	400	19	7.1	.55	.41
4	600	27	6.5	.52	.44
5	800	27	5.7	.58	.43
6	1000	23	6.1	.59	.49
7	1200	27	5.8	.59	.54
8	1400	26	5.7	.58	.57
9	1600	26	6.0	.57	.52
10	1800	26	6.0	.58	.57
11	2000	15	6.8	.62	.60
12	2200	10	7.0	.64	.61

factual notion of the size of the particles being studied. Field observations gave the impression that the over-all size of pebbles on the beach changed but little in the first 1600 feet of travel, with only slight diminution in size thereafter.

It will be noted that the mean sphericity increases slowly with distance of transportation, whereas mean roundness increases rapidly in the first 200 feet and more gradually thereafter. The total range of mean roundness values is 0.35, that of mean sphericity values only 0.09. It seems likely that were these samples from a conglomerate rather than a beach, and were the distance from their source not directly measurable, it would be easier to estimate the distance which the pebbles had traveled from their roundness than from their sphericity.

The data for mean sphericity and roundness from table 1 are plotted against distance in figures 4 and 5. The cause for the nonsystematic variation of Those sections of the roundness curve lying beyond the 1600-foot ordinate and between the 1100- and 1600-foot ordinates have similar slope and curvature, as if some material from the latter part of the beach had been moved along shore so quickly and directly that the customary amount of pebble wear had not been performed. The presence of a depression in the beach, formerly a gravel pit, which occupied 25 feet of its total 35-foot width at the 1600-foot station affords an explanation. It is possible that the removal of gravel from the pit upset the prevailing equilibrium between load and transporting ability of waves and currents in such a way that pebbles on the immediate up-current side of the pit were caused to move along shore at an accelerated rate.

The poorly defined linear trend apparent in the scatter diagram, figure 6, suggests that sphericity increases with roundness in only a general way.

APPLICABILITY OF THEORY OF ROUNDING

In recent studies of the properties of stream gravels (Krumbein, 1940, 1942) Krumbein observed that as a function of distance the roundness of pebbles increased in a systematic manner, rapidly at first and then at a decreasing rate such that some limiting roundness value was approached. Wentworth's Russel Fork field study (Wentworth, 1922) showed a similar relation of roundness to distance, as have experimental studies of the effects of abrasion on the rounding of rock fragments (Wentworth, 1919, and Krumbein, 1941b).

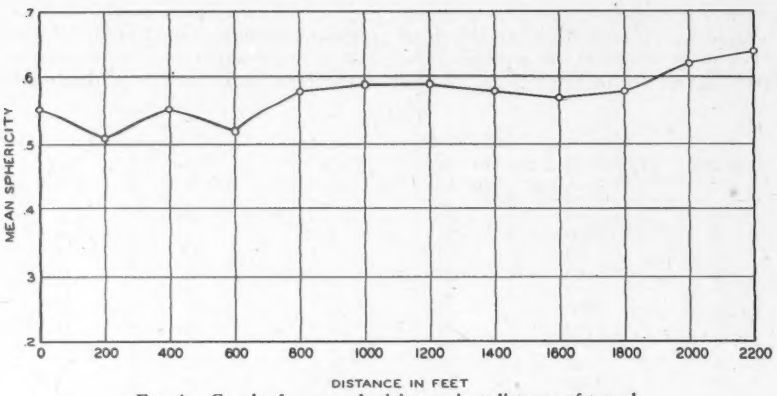

FIG. 4.—Graph of mean sphericity against distance of travel.

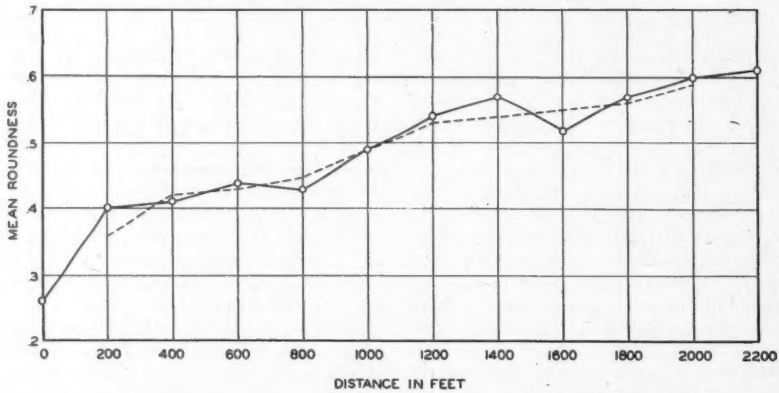

FIG. 5.—Graph of mean roundness against distance of travel. The dashed line represents a moving average of three successive measurements.

Krumbein has attempted to express this relation mathematically (Krumbein, 1940). Terming the roundess P, and the limiting roundness value P_0, he developed an equation of rounding which yields a

straight line when $P_0 - P/P_0$ is plotted on a logarithmic scale against distance on an arithmetic scale.

It was of interest to make a similar plot of the roundness data obtained in the present study to test the applicability of Krumbein's equation to the rounding of beach pebbles. A limiting value of roundness of $P_0 = 0.65$ was used as indicated by the curve in figure 5. The resulting fair degree of alignment of points shown in figure 7 can hardly be considered conclusive evidence, but does suggest that the rounding of beach pebbles proceeds in similar fashion to the rounding produced by streams and tumbling barrels.

Wentworth (Wentworth, 1919) found in his experimental study of the rounding of marble cubes that roundness increased to a maximum value and then began a steady slight decline, an effect which has not been observed in later studies. The writer has observed abundant rhyolite pebbles on beaches up to a mile distant (downcurrent) from the beach described in this paper, which were exceedingly well rounded and much flattened in accordance with the common tendency for beach pebbles to develop flattened discoid shapes, probably owing to unequal durability of rock fragments in certain directions and to the sliding nature of much of the movement of pebbles along shore. It therefore seems possible that studies of pebbles of a given size-group from more extended beaches might show roundness reaching and maintaining a maximum value while sphericity (volume or intercept) reached a maximum and then regressed slightly as the pebbles became thinner in proportion to their length and breadth. This is at least a feature to be looked for in future studies.

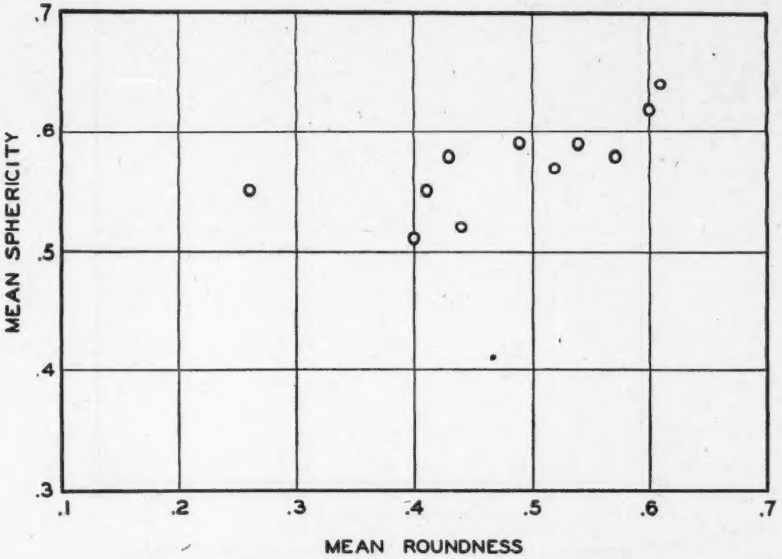

FIG. 6.—Scatter diagram of mean sphericity and mean roundness.

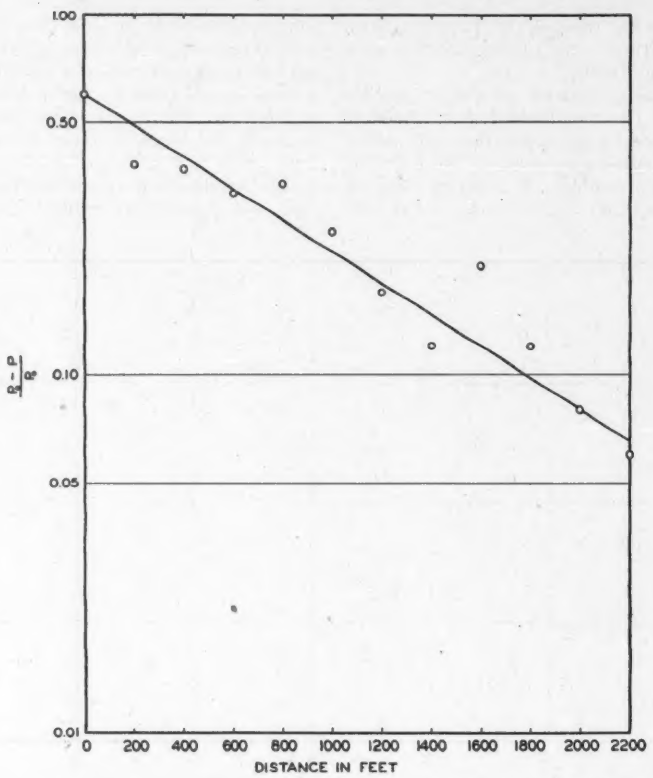

FIG. 7.—Graphic test of Krumbein rounding theory using beach pebble data.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 15, NO. 1, PP. 11–19
FIG. 1, TABLES 1–2, APRIL, 1945

HEAVY BLACK SANDS ON SOME VICTORIAN BEACHES

GEORGE BAKER
The University of Melbourne

ABSTRACT

The mineral compositions and grain size variations of the heavy black sands found on certain marine beaches in the State of Victoria, Australia, are described. The nature and positions of the heavy beach sands and the probable sources of their constituents are indicated.

INTRODUCTORY NOTE

Coastal sands have been exploited for their heavy mineral contents in several parts of the world, as for example at Jacksonville, in Florida, U.S.A. (D. M. Liddell, 1917; J. H. C. Martens, 1928; and H. Buttgenbach, 1921), Byron Bay in New South Wales (H. F. Whitworth, 1931, and W. R. Poole, 1939), etc. They are worked by means of a suction dredge and separated on tables and by magnetic methods for the recovery of minerals such as ilmenite, zircon, rutile and monazite.

Zircon-rutile-ilmenite-monazite sands are valuable constituents of heavy black sands, and Australia is one of the few countries producing them. There is a ready market for such sands in America, where there is a shortage of rutile, and where the Australian variety is sought after because of its good quality.

The minerals in the black sands recovered from beach deposits in New South Wales and Queensland are playing a considerable part in the conduct of the present war. Thus *zircon* is used for making refractory bricks for war factory furnaces; *rutile* is employed in the manufacture of paints, smoke screens and fluxes, while *monazite* is of value in the manufacture of tracer bullets and also in flints for automatic lighters (Industrial Australian and Mining Standard, 1944).

There are also manifold uses for the derivatives of the elements in these minerals. Zirconium metal is used as a photo flash powder. Zircon is used in rustless paint and fireproof cements, crucibles, vitreous enamels, armor-proof steel, explosives, sanitary and laboratory ware, porcelain insulators, opacities and abrasives. Rutile finds its use in titanium white paint, as a color and filler, as a glaze, as a component of spark plugs, artificial teeth, linoleums, ceramics, cosmetics, heat and shock resisting articles, wall papers and coated textiles. It is also used in chemical smoke clouds, sky writing, heavier-than-air poison gas, dye stripping, tanning leather and many other processes.

Occurrences in Victoria

Natural beach concentrates have not yet been found in sufficient quantities in Victoria to be of economic importance. Nevertheless, there are areas where natural panning and concentration of the heavy constituents of shore sands has occurred, and these are brought to the notice by virtue of their color. Whereas the majority of shore sands in Victoria are quartzose or calcareous, and consequently light in color as well as in weight, darker-colored patches ranging to dense black have been observed at St. Kilda, Aspendale, Rickett's Point, Davey's Bay, Canadian Bay and Mt. Martha, all of which are situated on the eastern shores of Port Phillip Bay, and at Balnarring on the western shores of Westernport Bay. On some of the ocean beaches, similar dark-colored streaks and patches have been noticed at Torquay, Sherbrook River, Loch Ard Gorge, Point Hayley

and Kilcunda (fig. 1). There are no doubt many other localities along the Victorian coast where the dark-colored shore sands are to be found in similar small quantities.

These heavy, black, shore sands are distinct from certain dark-colored beach deposits which occur in patches on some of the Phillip Island beaches in Western-port, where the dark color is due entirely

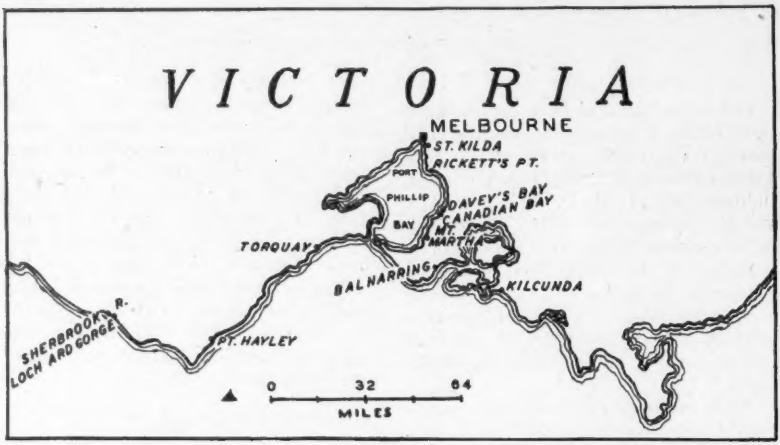

FIG. 1.—Sketch map of Victoria showing location of heavy black beach sands.

to an abundance of dark brown to black grains of ironstone (limonite, etc.) derived from the weathering of altered basalt lavas and tuffs forming the cliffs in the immediate vicinity. It is thus seen that all dark-colored beach sands are not of necessity composed of the dark-colored minerals which, when present in sufficient quantity, are of some economic importance; color is thus no conclusive guide in this respect. In like manner, black sands from the south-east coast of Iceland were shown to contain little heavy, opaque mineral matter (A. Stuart, 1927), but to be made up mostly of a brown glass.

In the opinion of P. G. H. Boswell (1933, p. 73), heavy detrital minerals tend to become concentrated as "pay streaks" where the velocity of the transporting agent is reduced; they are thus found at high-tide mark on beaches, or in the hollows of wind- or water-formed ripples, or in the vicinity of obstructions such as shells and pebbles which have the same effect as ripples in causing the heavy elements of shore sands to be locally concentrated. T. Crook and G. M. Davies (1909) recorded that at St. Ives Bay, Cornwall, tidal action resulted in a consistent concentration of heavier ingredients about high-water mark. These heavy ingredients occurred as streaked out bands, predominating for at least a foot beneath the surface. Few Victorian examples are as consistent as this occurrence. The ones discussed herein are beach concentrates of small lateral and vertical extent which come principally into the category of the 'high-tide mark type.' Some occur also as 'rill mark streaks,' but the location of all the occurrences is governed by tidal action, and does not remain constant. These heavy beach sands are thus water-sorted sediments in which wind has played little or

no part; they are not well-graded deposits, because well-graded sands contain only small quantities of heavy minerals. By virtue of their higher specific gravities, heavy detrital minerals, since they necessarily have the same "hydraulic value" as coarser grains of the lighter minerals, occur as grains of a grade size weight of 950 tons crude sand. At Davey's Bay, between Frankston and Mornington, several patches of black sands of nearly the same area as at Kilcunda are reported to have been periodically bagged and carted away for their TiO_2 content. These are of seasonal occurrence, being removed by flood tides or

TABLE 1

	Locality	Grain Size of Heavy Constituents in mm.		Ratio of Opaque to Colorless, Heavy Constituents
		Range	Average	Opaque Colorless
BAY BEACHES	St. Kilda	0 08–0.40	0.16	10:1
	Rickett's Point	0.08–0.32	0.14	5:1
	Davey's Bay	0.24–0.64	0.32	80:1
	Canadian Bay	0.24–0.94	0.40	60:1
	Mt. Martha	0.16–0.50	0.24	6:1
	Balnarring	0.08–0.56	0.16	4:1
OCEAN BEACHES	Torquay	0.14–0.48	0.24	5:1
	Sherbrook River	0.08–0.48	0.32	10:1
	Loch Ard Gorge	0.06–0.48	0.20	2:1
	Point Hayley	0.08–0.42	0.18	5:1
	Kilcunda	0.12–0.40	0.20	3:1

ranging from about one-eighth to one-quarter the size of the associated grains of lighter minerals. Variations in the velocity of the transporting agent in conjunction with the occurrence of local obstacles are responsible for the variability in the number of the coarser grained light minerals compared to the quantity of the heavier constituents in the heavy, black shore sands. Quartz is a minor ingredient of such concentrates, although on either side of the dark-colored streaks and patches, it is the principal constituent, except on beaches where the sand is composed mainly of comminuted shell waste.

The most extensive heavy, black shore sand among the Victorian examples cited above is that at Kilcunda, where the black sands cover an area of approximately 40×20 yd. and are up to 1 ft. thick. This would yield an estimated

covered over by sands of lighter weight and ligher color at various times of the year. The remaining Victorian examples referred to are of even more limited extent, occurring as small, narrow, rather infrequent streaks and patches a fraction of an inch thick, sometimes as veneers only one or two grains deep. The Rickett's Point occurrence is an example of this character. The heavy black sands here rested upon quartz and shell sands of much greater grade size. In a seaward direction, the black sands were in turn covered by a thin sprinkling of very fine quartz grains. The location of these small streaks and patches of heavy, black sands on the beaches of Port Phillip Bay is usually at high-tide mark and towards the centres of small bays. At Rickett's Point, they occur in such positions on the seaward side of a line of small pebbles.

The grain sizes of the heavier constitu-

ents of the sands are listed in table 1, together with the ratio of the opaque, dark-colored to the colorless heavy constituents. The proportion of heavy minerals to quartz and shell sand grains in the heavy beach sands varies from 50% to almost 100% of the deposits.

Equally fine grain sizes are met with among the heavy constituents from the beaches of Port Phillip Bay and Westernport Bay as from the ocean beaches. The general tendency is for heavy constituents on ocean beaches to range down to smaller grain sizes, and for those on the more sheltered bay side beaches to range up to coarser grain sizes, although the averages for each type are more or less similar. Grain size is controlled by several factors, chief among which is probably the dominant size of the grains or crystals in the source rock. Shore currents then effect the degree of sorting of the sands, and the heavier constituents become associated with a small number of grains of lighter minerals many times their average size because of marked specific gravity differences. As L. Hawkes and J. A. Smythe (1931) have shown, the size distribution of the minerals is governed by the specific gravities of the mineral species. The heavy minerals increase in amount with decrease in size, the light minerals and shell fragments decrease in amount with decrease in size. Apart from the presence of a few lighter colored, lightweight mineral grains such as quartz and feldspar, and apart from shell fragments, the color intensity of the heavy sands varies according to the proportion of the opaque, dark-colored to the colorless and light-colored heavy constituents. The manner in which this relationship can vary from place to place among the several occurrences of the heavy, black sands is indicated in table 1. Black grains are present almost to the complete exclusion of colorless heavy grains in the Canadian Bay assemblage from between Mornington and Frankston; it is unusual for the generally ubiquitous mineral species zircon to be absent, as in this instance, or for it to be as rare as in the nearby Davey Bay sample. In some examples, heavy colorless or pale colored ingredients are far more abundant, and the sand is then not nearly so dark in color. Samples which have a small ratio of opaque to colorless heavy constituents, such as in the Loch Ard Gorge assemblage, usually possess a considerable proportion of the lighter colored, lighter weight beach ingredients such as quartz and feldspar grains and comminuted shell waste.

The Heavy Minerals in the Dark-Colored Beach Sands

The various heavy minerals recognized from the several samples of heavy, black shore sands from Victorian beaches are set out in table 2, their presence in the sands being indicated with a cross. In addition to these minerals, one grain of tremolite was recognized in the Balnarring assemblage, one grain of ceylonite in the Kilcunda assemblage, while a certain amount of pyritic material in the St. Kilda assemblage was probably derived from the wrecked *Kakariki* nearby. (This ship was known to have been carrying a cargo of sulphide minerals.)

Separated by means of a magnetic separator, 150 grams of the Kilcunda heavy black sand showed 9.1% strongly magnetic fraction (magnetite), 64.9% moderately magnetic (principally ilmenite), 3.4% weakly magnetic (principally garnet, tourmaline, staurolite and monazite) and 22.6% non-magnetic (principally zircon and rutile, with a small amount of quartz).

Magnetite and ilmenite are the principal constituents of the black sands. The Torquay assemblage is made up principally of magnetite and zircon, while that from Rickett's Point is mainly ilmenite and zircon. Canadian Bay and Davey's Bay occurrences, which are only a few miles apart, have similar assemblages as far as the principal heavy minerals are concerned. The greatest assortment of heavy mineral species is found in the Balnarring, Loch Ard Gorge, Point Hayley and Kilcunda assemblages, but in

them, minerals like andalusite, brookite, cassiterite, cyanite, epidote, hornblende, hypersthene, monazite, spinel, staurolite, topaz, and blue to grayish colored tourmaline are represented by only a few grains of each. The Mt. Martha assemblage is composed chiefly of magnetite and ilmenite, likewise those from Canadian Bay, Davey's Bay, and St. Kilda. In the Sherbrook River example, a considerable proportion of the darker colored constituents is made up of limonite grains.

Rutile is next in abundance to magnetite, ilmenite and zircon, and is followed by garnet and tourmaline. The foxy-red colored variety of rutile always dominated the yellow-colored type. Yellow zircons are generally rare throughout, although they become relatively conspicuous in the Rickett's Point assemblage. Among the colorless zircons, rounded grains in most assemblages are approximately equal in quantity to examples showing well-preserved crystal edges and faces; the ratio of the two is variable in some assemblages, however, Rickett's Point, for example, showing zircons which principally have marked crystal boundaries and little evidence of rounding, whereas those in the Torquay assemblage are nearly all well rounded. Brown tourmaline dominates over the blue variety, and very rare parti-colored grains occur in the Sherbrook River assemblage. Pink garnet is rather more common than the brown and colorless types in assemblages containing the three.

Magnetite grains are mostly irregular in outline, well-rounded, spherical and ellipsoidal grains being uncommon, whereas octahedral crystals are rare. Ilmenite grains are often well rounded. Monazite, as oval, pale lemon yellow grains, is uncommon in all of the Victorian assemblages examined, although it has been recorded in some considerable quantity in beach deposits elsewhere in Australia. H. G. Raggatt (1925) recorded beach sands as containing monazite and as extending from Port Macquarie in New South Wales to the Queensland border, and L. C. Ball (1905) reported black sands on the beaches along the south coast of Queensland as containing monazite in association with gold, platinum and cassiterite, all of which are either rare or absent from the Victorian examples investigated. J. C. H. Mingaye (1903) also recorded monazite in the beach sands of the Richmond River in New South Wales, where gold, platinum, osmiridium, cassiterite, zircon and ilmenite accompanied the monazite.

Anatase is particularly rare in the Victorian heavy, black sand concentrates, occurring (see table 2) as one crystal (octahedral) only in each assemblage containing it. The augite occurs as both green and plum-colored angular grains, fractured along cleavage directions; garnets are principally represented by fracture fragments, rare examples showing crystal faces. Leucoxene is present both as individual grains and as sporadic patches on altered grains of ilmenite.

The degree of rounding of the heavy mineral species varies from mineral to mineral in the assemblages. The nature of the rounded grains depends mainly upon their hardness and their original crystal characters, especially form and cleavage. Rounded oval grains have resulted from long prismatic crystals, rounded grains approaching sphericity from cubic and short prismatic crystals. Irregularly-shaped grains, often with rounded protuberances, arose from original formless crystals or from fractured and cleaved types.

Probable Sources of the Constituents

It cannot be proved in all instances just whence the constituents of the various heavy, black sands were derived, because of the ubiquitous character of the more common of the mineral species; it has been possible to draw certain inferences, however, based upon the characteristics of heavy mineral assemblages as a whole. It is not possible to prove conclusively the number of cycles of erosion and transportation to which the heavy mineral suites have been subjected at each

TABLE 2

	St. Kilda	Rickett's Point	Davey's Bay	Canadian Bay	Mt. Martha	Balnarring	Torquay	Sherbrook River	Loch Ard Gorge	Point Hayley	Kilcunda
Anatase (yellow)	×	×	×								
Andalusite										×	×
Augite	×	×	×	×	×	×	×	×	×	×	×
Brookite											×
Cassiterite										×	×
Clinozoisite										×	×
Cyanite										×	×
Epidote										×	×
Garnet (colorless)	×	×	×	×	×	×	×	×	×	×	×
Garnet (brown)										×	×
Garnet (pink)										×	×
Hornblende										×	×
Hypersthene	×	×	×	×	×	×	×	×	×	×	×
Ilmenite	×	×	×	×	×	×	×	×	×	×	×
Leucoxene	×	×	×	×	×	×	×	×	×	×	×
Limonite	×	×	×	×	×	×	×	×	×	×	×
Magnetite	×	×	×	×	×	×	×	×	×	×	×
Monazite	×	×	×	×	×	×	×	×	×	×	×
Olivine	×	×	×	×	×	×	×	×	×	×	×
Rutile (red)	×	×	×	×	×	×	×	×	×	×	×
Rutile (yellow)	×	×	×	×	×	×	×	×	×	×	×
Sphene	×	×	×	×	×	×	×	×	×	×	×
Spinel (green)	×	×	×	×	×	×	×	×	×	×	×
Staurolite	×	×	×	×	×	×	×	×	×	×	×
Topaz	×	×	×	×	×	×	×	×	×	×	×
Tourmaline (blue)	×	×	×	×	×	×	×	×	×	×	×
Tourmaline (brown)	×	×	×	×	×	×	×	×	×	×	×
Zircon (yellow crystals)	×	×	×	×	×	×	×	×	×	×	×
Zircon (colorless crystals)	×	×	×	×	×	×	×	×	×	×	×
Zircon (colorless, rounded grains)	×	×	×	×	×	×	×	×	×	×	×

locality, but in some instances, it can be shown that certain distinctive mineral species, which appear in older geological formations, may have experienced five or more of these cycles. An element of doubt that becomes introduced into the problem, however, is due to the fact that whereas the distinctive mineral grains in older formations are well-rounded, the same mineral species in a younger formation may be represented as grains of a more angular to sub-angular character. J. Thoulet (1907), who conducted some experiments on the rounding of mineral particles, found that there was no obvious rounding or loss when minerals were placed in water in a cylinder and rotated for a distance equivalent to 170 kilometres. It may so happen, however, that by cracking and fracturing of brittle or easily cleavable minerals, rounded grains released from an older formation were broken and carried into a younger formation before again becoming well rounded.

The Port Campbell examples of the heavy shore sands, collected from the beach at the mouth of the Sherbrook River and from Carmichael's Cave in Loch Ard Gorge, respectively, contain mineral species found in the Pleistocene, Tertiary and Jurassic rocks of the neighboring coastline. These two examples of heavy beach sands, only one mile apart, have very similar assemblages of heavy minerals, and most of the constituent grains have doubtless been derived from the rocks forming the cliffs and wave-cut platforms in the district. Some of the minerals in the oldest of these rocks, i.e., in the Jurassic arkoses (A. B. Edwards and G. Baker, 1943), were probably derived from the Permian glacial deposits in Victoria, more particularly as these Permian deposits contain brown garnet, which has found its way into the Jurassic sediments and is wanting from Victorian Palaeozoic rocks older than the Permian. The source of the brown garnet in the Permian sediments is unknown; it most probably came from erratics brought in by glaciers from outside the State. Nevertheless, it appears probable that some of

the grains of this mineral have been subjected to at least five cycles of erosion and transportation—first from a pre-Permian source rock into the Permian, then from Permian into Jurassic arkoses, next from Jurassic into Tertiary deposits, from Tertiary into Pleistocene, and finally from Pleistocene into Recent beach sands. The degree of rounding of grains as found in the final stage of sedimentation is no sure criterion in establishing the probable length of time or distance travelled by abraded mineral particles, because fracture and collisional bruising, as well as flaking by the gradual opening up of cleavage planes during transportation, may have occurred at any time during the history of abrasion of any given heavy mineral particle. Other heavy minerals in the Jurassic rocks of this district, which ultimately found their way into the Recent beach sands, were derived from primary rocks of Devonian or early Carboniferous age in Victoria, and so have been subjected to probably four periods of erosion and sedimentation. Augite and olivine in the assemblages from the beaches near Port Campbell were probably brought down by streams draining basaltic areas 20 to 30 miles back from the coastline.

Some of the well-rounded, clear, colorless zircons of small size are like similar types in the Ordovician sandstones of Victoria. Since zircon is chemically and mechanically a stable mineral, it can have persisted into the Recent beach sands and thus survived as many as 7 or 8 cycles of erosion and transportation. On the other hand, many grains of this mineral may not have been released from the Ordovician sediments until much later in the earth's geological history.

In some parts of the world, it is considered that certain heavy mineral sands have been derived from the land by river action and concentrated on the shore by wind action alone. According to H. Buttgenbach (1921), the zirconiferous and titaniferous shore sands from between Jacksonville and Augustine in Florida have been derived in this manner. These sands extend for a distance of 1000 kilometres, but are only exploitable for about 50 kilometres, and they are said to have been derived from the Alleghany Mountains. The heavy constituents of the shore sands at St. Kilda, in Victoria, if the presence of augite is any guide, were probably derived from the country through which the River Yarra flows, the augite being released from weathered basaltic rocks in that district. There is an alternative possibility, however, that the augite could have been carried in by wind from farther afield, likewise the olivine present, especially as these two minerals are by no means common among the heavy minerals of this assemblage; moreover, olivine and augite have both been recognized among the constituents of the red dust storms that occasionally sweep across the State.

In other parts of the world, it seems that certain heavy constituents of sandy beaches along coastlines have been derived immediately from the rocks in the vicinity. Thus, titaniferous-iron sands on the foreshore at Porth Dinlleyn, on the Carnarvon coast, occur near the so-called serpentine outcropping there. According to T. H. Cope (1902), the common quartzose sand of the foreshore suddenly changes in character to a deposit of black sand, 31 ft. long, 5 ft. wide, and 3½ inches in depth. The wealth of heavy minerals and similarity of species in the Recent heavy shore sands from Point Hayley (near Apollo Bay) and Kilcunda are striking. These are localities which are many miles apart. Each of the beach assemblages, which are in close proximity to Jurassic arkoses, have marked similarities to the assemblages of the Jurassic sediments (see A. B. Edwards and G. Baker, 1943, p. 201). This fact points to the strong probability of the derivation of heavy minerals in the beach concentrates from the Jurassic arkoses which form the sea cliffs and the hinterland in these two districts. Some of the ilmenite and magnetite in the Kilcunda heavy, black beach sand, however, was derived from nearby olivine basalt dykes which

transect the Jurassic sediments.

The principal contributors to the heavy beach sand at Torquay were probably the Tertiary rocks of the neighboring coastline. These were apparently rocks containing only sporadic heavy minerals of but few varietal species; the minerals found in the shore sands derived from them have no particular discriminating value, being of a usually ubiquitous character.

The dark-colored heavy ingredients of the shore sands from Davey's Bay and Canadian Bay probably had their source partly in the granodiorite outcropping along the cliffs at Oliver's Hill near Frankston (G. Baker, 1942), and partly in the ferruginous Tertiary deposits forming prominent cliffs in the neighborhood of each of these bays. Likewise at Mt. Martha beach, the heavy dark sands came principally from the coastline and hinterland formed by the Mt. Martha granodiorite (G. Baker, 1942), and associated metamorphosed Ordovician sediments, because the types of zircon and tourmaline in the shore sands are of comparable character to those in the heavy mineral assemblages of the coastal rocks.

At Rickett's Point, the heavy constituents in the small streaks and patches of heavy, black sands on the beach were principally derived from the Tertiary Red Beds of the district. The Balnarring assemblage of heavy constituents appears to have been derived from a mixture of source rocks such as Tertiary basalt, Devonian granitic rocks and their associated metamorphosed sediments, as well as later unaltered sediments which go to make up the hinterland and islands of Westernport Bay.

Submarine outcrops, however, on the nature of which we have little information, may have contributed in some considerable measure to present day shore sands at the localities dealt with. De Limur (1878) showed that heavy minerals in the shore sand at Penestin had drifted there, possibly from submarine outcrops, under the influence of currents caused by equinoctial gales, and had not been derived from the cliffs above. Also J. Thoulet (1907) ascribed the transport of minerals of Bréton origin into shore sands of the Pas de Calais, 200 to 300 kilometres distant, as due to longshore drift and wave action. It is therefore seen that mineral constituents in shore sands can be quite alien to those in the rocks of immediate and neighboring coastal districts. However, the general similarities of certain of the mineral species in the Victorian heavy, black shore sands to those in the different rocks of the neighboring coastlines at the localities from which the samples were collected, are deemed sufficiently distinctive to uphold the broad generalizations which have been made concerning the probable source rocks. In like manner, H. F. Whitworth (1931) came to the conclusion that the heavy constituents of the natural beach concentrates of New South Wales had their origin in the Triassic sandstones near Sydney and the Upper Coal Measure sandstones near Muswelbrook, except for gold and platinum, the origin of which remains doubtful.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 15, NO. 1, PP. 20–24
FIGS. 1–6, APRIL, 1945

UNUSUAL NUCLEI IN OÖLITES FROM THE MORROW GROUP NEAR FAYETTEVILLE, ARKANSAS[1]

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ABSTRACT

Oölites whose nuclei seem to consist of enhedral quartz crystals are found in a limestone bed of the Hale formation, lower Pennsylvanian age, near Fayetteville, Arkansas. The true character and origin of these nuclei are manifested most clearly in thin section if lighted by a darkfield condenser. The nuclei consist of two parts. The inner part has the size and shape of ordinary sand grains. The outer part, which bears the crystal faces, contains a faint ghost structure that (1) resembles and connects with the radial and concentric structure in the concretionary zone of the oölite, (2) conforms to the irregular shape of the inner part of the crystal, and (3) is obviously a residue of previously existing calcareous oölite structure. The inner part was originally a quartz sand grain that served first as the nucleus of the calcareous oölite and again, at a much later time, as the nucleus for the silica that replaced a part of the calcareous oölite. The source of the silica is obscure.

LOCATION AND STRATIGRAPHIC POSITION

In 1935, while engaged in field work on the Morrow group of the Ozark region, a bed of oölitic limestone was found whose grains have euhedral quartz-crystal nuclei.

The oölite outcrops on the east side of Mount Sequoyah (formerly East Mountain) about 30 yards north of the center of the south line, SW¼SW¼ sec. 11, T. 16 N., R. 30 W., Fayetteville quadrangle, Washington County, Arkansas.

The bed lies in the upper part of the Hale formation of the Morrow group, Pennsylvanian. The oölite is but a few feet thick and is probably only a local phase of the series of limestone, calcareous sandstone, and cross-bedded marine clastic beds that compose the upper part of the Hale in this region and that have locally been confused with the overlying Brentwood limestone member of the Bloyd shale. Oölitic limestone is not unusual at this horizon and may be found locally developed at a few other places. A locality worthy of mention and easily accessible exists on the south side of Mill Creek, at the cut along U. S. Highway 71, due north of Pitkin (Woolsey) Station, Washington County. As a result of similarity between this limestone in the Hale formation and parts of the underlying Pitkin limestone of Mississippian age and as a result of apparent continuity of the outcrops of the Hale and Pitkin in this vicinity, the limestone in the Hale formation was erroneously mapped for a distance of about 1½ miles in sec. 16, T. 14 N., R. 30 W., and SW¼ sec. 9, T. 14 N., R. 30 W., as Pitkin limestone (A. H. Purdue, U. S. Geol. Survey Geol. Atlas, Winslow folio (no. 154), 1907). At this locality as elsewhere the oölitic phases of the limestone are not prominently developed.

[1] Published by permission of the Director of the Geological Survey.

LITHOLOGIC FEATURES

The limestone is light-gray, matte, compact, and has medium texture. Spaces between the oölite grains are filled with fine-textured calcium carbonate. The oölite grains are generally as closely packed as they can lie. The majority of the oölite grains are spherical or nearly spherical, but a considerable number have irregular shapes as a result of conforming to larger than average, odd-shaped nuclei. The concretionary parts of the nuclei and the matrix are relatively

pure limestone. Rather widely scattered specimens of *Endothyra* sp. and *Millerella* sp. are present. Fragments of invertebrate shells are common and are generally reduced to the size of sand grains.

The lithologic character of the oölite and associated beds is highly variable in this region. Individual limestone beds ordinarily have but local distribution, as would be expected from the variable nature of the rock and from the irregular to cross-bedded structure of the sediments.

The associated limestone beds of the Hale formation are characterized locally by prolific marine invertebrate faunas, though fossils are generally scarce in the oölite beds. Foraminifera and fragments recognizable as bryozoans and echinoderm ossicles are present in the oölite. Marine origin is therefore indicated. The oölite beds are commonly cross- or irregularly bedded. So much of the other limestone and marine sandstone at this general horizon has cross-lamination, cut-and-fill bedding, clastic constituence, and great local variation in thickness and microscopic character that deposition in the shallow-water zone of wave and current action is strongly indicated.

INTERNAL STRUCTURE OF THE OÖLITE GRAINS

The size of most of the oölite grains ranges from 0.55 to 0.65 mm. in diameter. The average diameter of the great majority is 0.60 mm.; so the size is not at all unusual. Radial and concentric structure typical of oölite grains is exceedingly well developed.

The majority of the nuclei are short crystals of quartz. They are terminated by pyramids and are entirely unabraded (pl. 1, fig. 4). A considerable number of nuclei consists of various fossil fragments, rarely including entire shells of the foraminifers *Endothyra* and *Millerella*. A very few are rounded grains of quartz, fragments of hard shale, or are indeterminable.

Rocks of this age are so rarely chertified in the Ozark region and contain so little secondary mineralization that the presence of crystal nuclei in these moderately lithified, almost undisturbed rocks is surprising. Thin sections were therefore prepared and carefully examined to determine the history of these grains. With the aid of polarized light and of dark- and bright-field illumination, the following observations were made on the crystal nuclei. Many crystal nuclei not merely occupy the center of the grain but extend to the outside of the grain or even a short distance beyond. The crystal faces generally cut across the concentric and radial structures that are so well developed in these oölites and that are characteristic of oölites in general. In none of the grains is there a tendency for the concentric growth bands of the oölite to conform to the shape of the crystal nucleus, as they almost invariably do to the shape of ordinary nuclei.

It was observed in many grains, particularly by dark-field illumination, that the concentric and radiating bands in the oölite grain are continuous with faintly visible inclusions that have a similar structure in the outer part of the crystal. Furthermore, these inclusions not only display a concentric and radiating structure that is characteristic of the concretionary zone of oölites, but they conform to the shape of a more or less rounded nucleus within the crystal. This nucleus is free of such inclusions. By examining a large number of crystal nuclei with various kinds of illumination it became clearly evident that the crystals consist of two parts, (1) an inner, more or less rounded grain of quartz and (2) an outer quartz mass that bears the crystal faces and contains the faint ghost-like residue of the oölite structure. The optical orientation of the inner and outer parts of the crystal is the same. Very commonly peculiarities in the optical and crystal structure of the inner part are continued into the outer part of the crystal. The union between the inner and outer parts is generally so good that it often requires a trial of different modes of illumination to detect the boundary. The inner part commonly con-

tains inclusions or local imperfections and irregularities that do not continue into the outer part. The inner part of the crystal resembles average quartz sand as to such general characteristics of rounding as the abrasion of prominent points and the absence of abrasion in depressions or minute recesses.

From these several observations it is obvious that the ghost oölite structure in the outer part of the crystal is a residue *in situ* of material that was originally a part of the oölite. All of these observations agree in indicating that the inner part of the crystal is the true nucleus of the oölite and that the outer part of the crystal was added after the oölite was formed.

In time of origin the different parts of this oölitic limestone came into their present state in the following sequence (see pl. 1): first, the quartz sand grains and other fragments that served as nuclei; second, the formation of the oölite accretion; third, partial if not locally complete filling of the spaces between the oölite grains with fine lime mud; fourth, the addition of crystalline quartz to the nucleus through partial replacement of the oölite grain.

The evidence for placing most of the filling of the interstices as the third event is fragmentary. Actually this event has probably progressed from the time that lime mud, formed in part from wave-ground oölite grains, settled down between the new deposit of oölite lime sand. It seems likely that the last pore space in the matrix was filled by the calcium carbonate displaced by the growth of the quartz crystals. A portion of the matrix is composed of fine crystals of carbonate. The observations that (1) the nuclear crystals that extend through the outside of the grains into the matrix as well as the very few that grew from the matrix into oölites do not change form at the boundary of the oölite and (2) the observation that some crystal faces that over a considerable area lacked but 3 to 5 microns of extending to the outside of the oölite did not burst the wall suggests that the wall was supported by matrix which had filled the spaces before the crystals began growing.

The replacement evidently took place with a minimum of displacement of the insoluble residues. The slight turbulence of this chemical action is evident in the fine preservation of the ghost oölite structure in the crystal and in the general absence or small amount of segregation of the insoluble residues around the outside of the crystal. I have rarely seen less segregation in the silicification of calcareous shells of Foraminifera. One of the interesting features of the replacement is the apparently small amount or absence of bursting of the oölites as a result of the growth of the quartz crystal. A number of the oölite grains are slightly ruptured and some are partly crushed, but it is not entirely certain whether the rupturing is a result of pressure from outside the rock. Some crushing is certainly a result of the compression of one grain against another, but it is possible, of course, that this compression may actually be the result of

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PLATE 1

FIGS. 1–2.—Same area. *1*, Crossed *Pola* screens, ×44; *2*, normal brightfield illumination, ×45.

FIG. 3.—Crossed *Pola* screens, ×45.

FIG. 4.—Quartz crystal nuclei isolated with HCl. Specimens were mounted on a glass slide, coated rather heavily with sublimated NH_4Cl, and photographed with a ring illuminator designed especially for illuminating the external features of Foraminifera and similar minute objects. ×13.

FIGS. 5–6.—Same area in both pictures. *5*, Crossed *Pola* screen, ×45; *6*, darkfield illumination, ×54. Darkfield shows the faint ghost structure in the replaced part of the oölite more conspicuously than any other kind of lighting, but gives the poorest resolution in the original part.

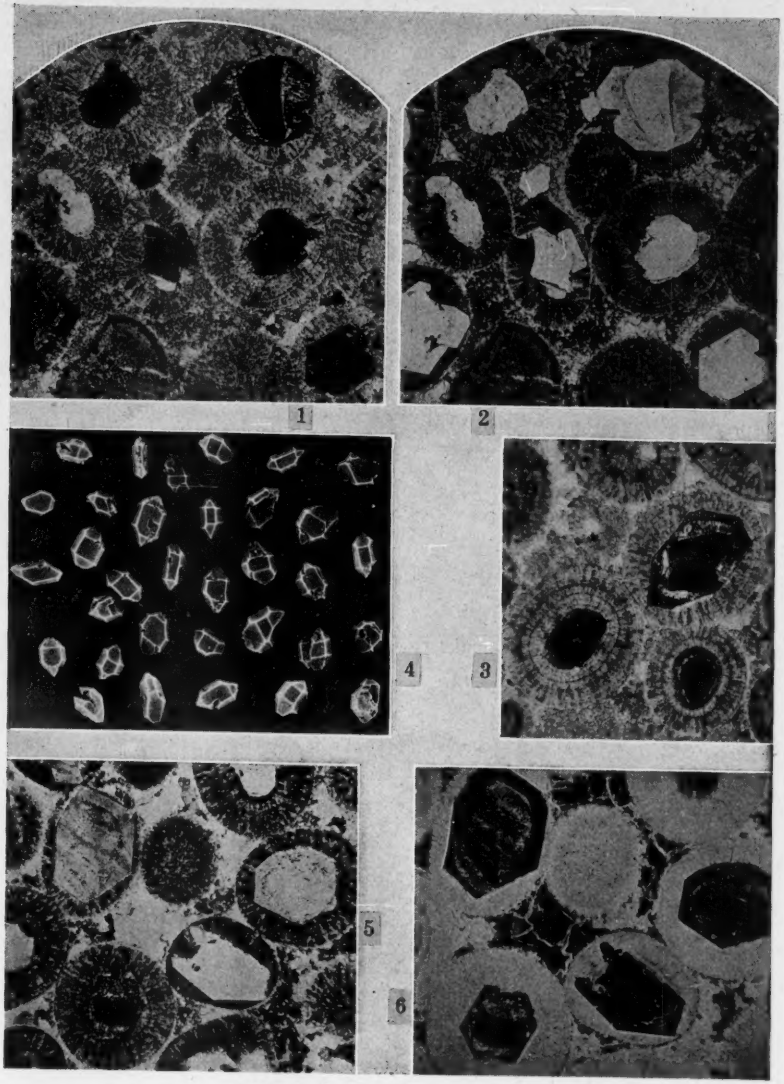

PLATE 1

(See opposite page for legend)

internal expansion within a confined space rather than of active pressure from a source outside the rock mass.

SOURCE OF THE SILICA

The source of the silica remains obscure. Mineralized veins or veinlets are lacking not only in the immediate deposit but in the vicinity. No chertification nor quartz druses were observed thereabouts. The limestone of the Hale formation in this region is separated from the underlying Mississippian cherty limestones by unsilicified limestones and shales and sandstones that include 200 to 450 feet of black, very impervious shale. For these reasons a source from within the rock is suspected. So far no arkose, ash, or siliceous spicules and tests such as those of Radiolaria and sponges have been observed in this rock, but as it is my opinion that volcanic ash is a far more common and widespread constituent of marine sediments than commonly supposed, I suspect that ash will be found to be the immediate source of this silica.

Since the above paper was written, two other examples of secondary enlargement of oölite nuclei have been found in the Morrow group. One occurs near the top of the Morrow group in Washington County, Arkansas, and the other near the base in Oklahoma. Both examples have a complicated history. The latter is involved with microscopic stylolites between oölite grains. These are to be described at a later date.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 15, NO. 1, PP. 25–33
FIGS. 1–3, APRIL, 1945

CLAY-PELLET CONGLOMERATES AT HOBART BUTTE, LANE COUNTY, OREGON[1]

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ABSTRACT

Ovate pellets of kaolinite from .05 to 15 millimeters in length occur in conglomerates interbedded with pyroclastic materials and waterlaid sediments in the Eocene Calapooya formation at Hobart Butte, Oregon. Although Miocene hydrothermal solutions invaded these rocks, altered welded tuffs to clay, and deposited kaolin minerals together with realgar, stibnite, pyrite, quartz, and other minerals, a hydrothermal or a volcanic origin for the pellets is considered unlikely. The sizes and shapes of the pellets, the presence of pellets and lithic fragments within pellets, the lack of radial and concentric structures, the presence of charcoal, lignitic material, and diatoms in the matrix suggest fluvial deposition of clay flakes, broken from thin clay layers that had dried on Eocene flood plains. The arrangement of the long axes of the pellets parallel to the bedding and the molding of pellets against quartz, lithic fragments, and pellets support the interpretation of a sedimentary origin for the pellets and the clays containing them.

INTRODUCTION

Hobart Butte is in Lane and Douglas Counties, Oregon, approximately 14 miles south of Cottage Grove and about 1 mile from the town of London. During 1943 Hobart Butte was prospected as a source of high-alumina clay by the United States Bureau of Mines in cooperation with the United States Geological Survey. The diamond drilling showed it to be one of the best high-alumina clay deposits in the Northwest. More than 10 million tons of ore with approximately 29 per cent available Al_2O_3 were proved.

The rocks of Hobart Butte are composed of pyroclastic materials and high-alumina water-laid sediments belonging to the Calapooya formation of Eocene age (Wells and Waters, 1934). These rocks were invaded by hydrothermal solutions, probably in late Miocene time (Wells and Waters, 1934, p. 25; Callaghan and Buddington, 1938), and realgar, stibnite, arsenates, pyrite, quartz, dickite, and other minerals were deposited.

[1] Published by permission of the Director, Geological Survey, United States Department of the Interior.

Wilson and Treasher (1938, p. 18), as well as others, were impressed with the presence of the hydrothermal minerals and concluded that the kaolinite was also of hydrothermal origin. The presence of dickite and of welded tuffs which are now altered to high-alumina rocks indicates that some of the clay did result from hydrothermal activity. One of the most interesting and abundant rock types on the Butte contains ovate clay-pellets. Because these present significant evidence of the genesis of much of the high-alumina clay of Hobart Butte, they will be described and various theories for their origin will be considered.

DESCRIPTION OF PELLETS

Clay-pellet rocks are well exposed at Hobart Butte. They have been briefly described by Wilson and Treasher (1938, pp. 71 and 73), who called the pellets "white bodies" and white "oolites." These pellets are, in general, irregular spheroids with elliptical cross-sections. The long axes are parallel to the bedding and they range in length from 15 millimeters to less than .05 millimeter (fig. 1). Based on the measurement of 47 pellets, the average ratio of the long axes to the

short axes is 2.4; the smallest ratio is 1.5, and the greatest 4.1. In one of the slides studied the area of the pellets was approximately 33 per cent of the total; however, in some specimens of the rock it is probably as low as 10 and in others as high as 75 per cent. The variation, moreover, is not systematic.

Most pellets occur as single and separate individuals. Some are molded against each other, against small pieces of charcoal, or against quartz grains or lithic fragments of silicified volcanic rocks. This molding suggests that the pellets were somewhat plastic at the time of formation. Pellets within pellets are not rare and one large one contains 20 small ones. Small siderite concretions have been found inside a few of the pellets and fine-grained pyrite is locally scattered through them. The pyrite was deposited by hydrothermal solutions and the siderite by either hydrothermal solutions or ground water. A few pellets have black hard cores which in some are pyrite, in others lithic fragments. One pellet contains 2 lithic fragments. A small amount of lithic material of microscopic size is also scattered through the matrix. Some of the pellets have small limonitic spheroids scattered through them, which may have resulted from the oxidation of small siderite concretions or pyrite grains, and others are uniformly stained yellow or brown by limonite. They are in general megascopically homogeneous although one zoned pellet was observed. The center of this pellet is light gray and the margin is white. Some of them have a mottled blotchy appearance resulting from an irregular distribution of white and gray fine-grained material. No radial structures were observed in any of the pellets, they are not composed of stratified material, and they cannot be broken out of the matrix.

A pellet 4.0 millimeters in length was observed which was faulted through the center in a plane perpendicular to bedding. The displacement was about .6 millimeter and the trace of the fault plane could be followed for about 12 millimeters. This is apparently an example of contemporaneous faulting and if due to a drying out of the sediment would suggest a shallow water environment for deposition.

The matrix is fine-grained kaolinite, shows no megascopic stratification, and is usually white, light gray, dark gray, light brown, or red in color. Microscopic study reveals many brown stringers parallel to the bedding and apparently of lignitic material. In some specimens the laminae curve over as well as under the pellets. Diatoms and fragments of charcoal, some of which are as large as the pellets, are also found in the matrix. On heating such specimens dark fumes originating from carbonaceous materials are given off. The pellets are white or light gray in color. They are lighter than the matrix and, where the matrix is red, the pellets are white and sharply differentiated from it. Some of the pellet rock bleaches on exposure to air. This is especially noticeable when the pellet rock which has long been exposed is compared with that freshly broken. The rock that bleaches has a brown matrix which may owe its color in part to lignite. Similar rocks at Castle Rock, Washington, also became bleached on exposure to air. The pellets have an apparent hardness of approximately 2, the matrix is somewhat softer, and the rock breaks with a conchoidal fracture. The specific gravity ranges from 2.28 to 2.38, depending upon porosity and the quantity of siderite, sulphides, and carbonaceous material present.

Lithic fragments of megascopic size are rare. Scattered through the clay-pellet rocks in the quarry, however, are a few rounded light colored porous rock structures from a fraction of a centimeter to 10 centimeters in diameter. They are soft, have a low specific gravity, a porous texture, and are very friable—so much so that some of them crumble on a free face and fall out leaving holes in the rock. In some, the pellets close to these structures are parallel to their surfaces, but a short distance away are as usual parallel to the

bedding. These structures might be assumed to be fragments of pumice, but no vesicles, glass threads (Pele's hair), or other features characteristic of pumice could be identified with a hand lens or in thin section. Porous rock, resulting from hydrothermal activity and with realgar or siderite filling some cavities, occurs in the quarry. The relict pellet structure of the walls of the cavities suggests that the porous texture of other areas may also be due to hydrothermal leaching of included fragments or parts of the matrix which had high permeability and susceptibility to the invading solutions.

Calculation indicates that the porosity in some of the clay-pellet rock may be as high as 13 per cent. That it has some permeability is indicated by the penetration of water into a dry specimen. Several observations indicate that the pellets are less pervious than the matrix. In places the matrix is thoroughly stained with limonite while the pellets are either unstained or only slightly stained. Siderite is abundant in the matrix but is sparse in the pellets. About half way up the quarry face is a pronounced band of realgar which has replaced the matrix but not the pellets. The pinnacle on the south side of Hobart Butte is composed in part of a rock that has white clay pellets and a hard siliceous matrix. Apparently a clay-pellet rock has been silicified by hydrothermal solutions. The pellets being relatively impervious were not silicified, while the more pervious matrix was. A similar rock was found on the southwest end of the Butte.

The organic matter in three samples of pellet rock from the Hobart Butte quarry was determined by W. W. Brannock in the chemical laboratory of the Geological Survey, U. S. Department of the Interior. One with white pellets in a brownish matrix (figs. 1 and 3a) from near the top of the quarry contains 1.31 per cent organic matter. Another with white pellets in a darker matrix has 2.80 per cent, and the lower clay of the quarry, composed of elongate white fragments in a gray matrix (fig. 3c), contains .31 per cent organic matter. When the organic material is not determined separately it is included in the ignition loss. Consequently, in the Hobart Butte samples for which the reported ignition loss is higher than normal, the presence of some organic matter is also suggested. As observed by Wilson and Treasher (1938, p. 71), the gray color due to finely divided carbon burns out on firing. Examination of fragments that have been fired reveals that the pellets remain white whereas the matrix is streaked by an irregular red network where appreciable iron in the clay has been oxidized during the burning. This suggests that the iron content of the matrix is higher than that of the pellets, which is certainly true where the pellets are white and the matrix is red.

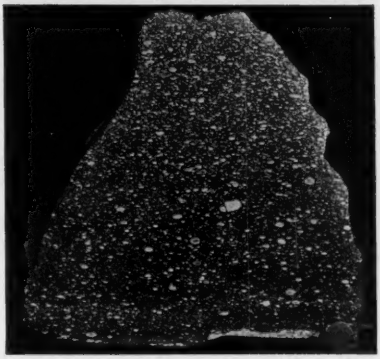

FIG. 1.—Pellet conglomerate, consisting of white pellets in a gray matrix, from a ten foot layer at the Hobart Butte Quarry, Oregon.

Petrographic study indicates that the pellets are composed of kaolinite, some of which is present as micaceous plates forming small worm-like areas or books. Kaolinite also replaces the glass of pumice fragments that are included along with white pellets of kaolinite in a red or purple matrix. Locally, a few per cent of a brown stained clay mineral with low to moderate birefringence and wavy extinction, that may be montmorillonite, occurs as wisps in the matrix, but mont-

morillonite could not be definitely established as a minor constituent of the Hobart Butte clay by either optical or chemical methods. According to the determinations of J. M. Axelrod of the Geological Survey kaolinite is the only clay mineral recorded in the X-ray patterns of ground samples representing both the pellets and the matrix. Also, the X-ray determinations reveal that the red color of the matrix surrounding the white pellets is caused by hematite in some samples and goethite in others. X-ray diffraction lines representing quartz are present in the patterns of nearly all the Hobart Butte clays examined. On the basis of thermal analyses Dr. Joseph A. Pask of the Federal Bureau of Mines finds that the pellets are kaolinite and in general are purer than the matrix.

The best place to see these pellets is in the main part of the quarry, about half way up the face (fig. 2). Here there is a 10 foot layer of rock in which they are abundant. Clay-pellet rocks occur elsewhere on the Butte and they are important constituents of the diamond drill cores.

ORIGIN OF PELLETS

Before it was established that organic material forms an essential part of the matrix surrounding the pellets, many theories of origin for these structures were proposed or considered by geologists who had visited Hobart Butte. The presence of organic matter in the matrix is regarded by the writers as convincing evidence for the rejection of all theories except those involving sedimentation. However, to avoid repetition only those arguments based on other evidence than the presence of organic matter will be briefly stated in reviewing the theories which follow.

It has been suggested that the rock in which the pellets are found was originally vesicular, that the clay pellets are filled vesicular cavities, and that the high kaolinitic composition is due to hydrothermal alteration (Wilson and Treasher, 1938, p. 73). It is unlikely, however, that this is an altered amygdaloidal rock because: 1. No relict igneous textures are present in the matrix. 2. There is no concentration of pellets at the top of the clay-pellet horizon such as would be expected if these were amygdules in an uneroded flow. 3. There is no disconformity at the top, which would be expected if the clay-pellet rock were an eroded lava flow. 4. The pellets are too regular and simple in shape.

The pellets are not hydrothermally altered spherulites, formed in lava or incorporated in a spherulitic tuff under some specially controlled conditions of crystallization and eruption, for the following reasons: 1. No relict spherulitic texture is apparent in the pellets. 2. No relict igneous textures can be seen in the matrix. 3. The presence of pellets and lithic fragments within pellets is left unexplained.

It has been suggested that the pellets are feldspar crystals altered by hydrothermal activity. This necessitates that the clay-pellet rock is either an altered porphyry, an altered crystal tuff, an altered reworked crystal tuff, or an altered arkose. The presence of pellets and lithic fragments within pellets, as well as the thickness of the clay-pellet rock, and the lack of relict igneous textures in the matrix all indicate that the rock is not an uneroded porphyry. Some modification in the shapes of phenocrysts might result from hydrothermal alteration, but it is unlikely that shapes similar to those of the pellets would be produced. Likewise, the shape and molding of the pellets and the presence of pellets and lithic fragments within pellets exclude the derivation of the clay-pellet rock directly by alteration of a crystal tuff, a reworked crystal tuff or arkose. Moreover according to Harker (Harker, 1935) the long axes of some crystals in a crytal tuff may be roughly perpendicular to the bedding. The long axes of the pellets are parallel to the bedding, which is further evidence that the rock is not an altered crystal tuff.

The Hobart Butte pellets might be ac-

FIG. 2.—Hobart Butte quarry, Oregon. Bedding in the clay is shown at the left center, where pellets are abundant.

cretionary lapilli (volcanic pisolites) that have been hydrothermally altered to kaolinite (Wentworth and Williams, 1932). Accretionary lapilli have been found around active volcanoes; they have been described from the Triassic of New Zealand (Perret, 1924, 1913; Pratt, 1916; Richards and Bryan, 1927); and they have many characteristics that are similar to those of the pellets. Pellets within pellets, lithic fragments within pellets, the shape and orientation, the molding of pellets against pellets, and many other features could be explained if they were formed in this way. The general geologic setting seems favorable for such an origin because welded tuffs have been found stratigraphically only a few hundred feet above the clay-pellet rock and the Calapooya formation, in general, contains much volcanic material (Wells and Waters, 1934). It is thought, however, that the Hobart pellets were not formed in this way because the relict textures, that might be expected in the matrix and within the pellets according to such a theory, are not present; furthermore, the Hobart pellets are not concentrically layered as are accretionary lapilli.

The shapes of these pellets of course eliminate the possibility that they are hydrothermally altered stream pebbles or lapilli.

Faecal pellets found in modern marine sediments have been illustrated and discussed by Moore (Moore, 1939) and they have been found in California oil shales of Miocene age (Galliher, 1932). Some of those illustrated by Moore (Moore, 1939, p. 520) are identical in shape with some of the pellets found at Hobart Butte. The pellets at Hobart Butte, however, are not faecal pellets as they are much too large, they are in continental rather than marine rocks, and they vary too much in shape and size.

The pellets under discussion are not syngenetic concretions formed by colloidal deposition because: 1. A study of the red beds on the Butte and elsewhere in the district indicates that the red color is original and is not the result of hydrothermal activity, which tends to remove ferric iron rather than to deposit it; as a matter of fact the hydrothermal solutions have in places bleached some of the red beds. If, therefore, the white pellets in the rock with the red matrix were formed by colloidal deposition, they should be red rather than white. 2. Pellets and lithic fragments within pellets, on the hypothesis of colloidal deposition, could be explained if the growing concretion is rotated. Conditions that would favor rotation, however, would be unfavorable for colloidal deposition. 3. The subangular outline of some of the pellets is not in harmony with the shapes resulting from settling from colloidal suspension. 4. In a discussion on mud pebbles Twenhofel (1939) states, "They are rarely, if ever, due to the union of suspended particles of mud."

The pellets are not epigenetic concretions formed after the deposition of the enclosed rock by substances derived from within or outside of the rock. It has been noted that the pellets and the matrix are both composed of kaolinite, but the pellets are purer and lighter in color than the matrix. If substances were removed from the pellets to increase the purity of the kaolinite comprising them, the permeability of the pellets should have increased in proportion to the amount of impurities removed. The effect of this action was slight, as the pellets are less permeable than the matrix. Moreover, since kaolinite has low solubility in ground water and since the deposition of any substance except kaolinite within the pellets to cause a contrast in color would decrease the purity of the pellets as compared with that of the matrix, the possibility of the formation of the pellets as a concretionary process by ground water action is remote.

The writers' interpretation is that these rocks were formed by processes of sedimentation similar to those described by Allen (1932), Fenton (1937) and others, for intraformational conglomerates, mud-conglomerates, mud-cake conglomerates, desiccation conglomerates, and flat-pebble conglomerates. The pellets are of intraformational origin and because most of them are small and round the name clay-pellet conglomerate or clay-pellet shale, depending upon the abundance of pellets, seems appropriate. They were probably formed somewhat as follows: Thin layers of clay were laid down on flood plains, the clay was dried out, and later the clay flakes, formed by the drying, were broken, picked up, and transported to their present position by running water. During transportation they were rounded by molding, sloughing, attrition, and perhaps also by accretion so that fragments of considerable initial angularity were changed into well rounded pellets. Finally the pellets were deposited together with clay, charcoal, organic material, and a small percentage of lithic and mineral fragments. That the pellets, in general, only slightly resemble the initial flakes indicates the effectiveness of these processes. Mud-flake breccias were seen in the drill cores and here the rounding processes were not so effective.

Some of the clay deposited at Hobart Butte apparently had a strong tendency to break up in water or crack in air on drying and yield ovate fragments which would require little or no modification during transportation to duplicate the shapes of the pellets. In the gray clays at the bottom of the quarry are many white kaolinite fragments that are separated from each other by clay containing organic matter and slightly more iron than that present in the white fragments. Many of these rudely ovate fragments fit together perfectly (fig. 3c) and suggest that they were broken apart in water and that fine clay with organic matter and appreciable iron washed into the cracks. It is conceivable that similar spalling

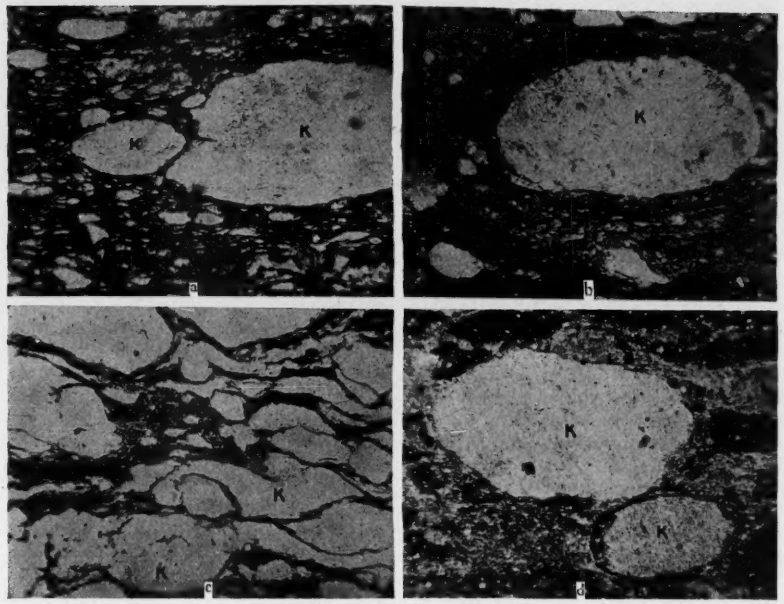

FIG. 3.—Photomicrographs of pellet structure in clay.

a—Kaolinite pellets (K) surrounded by clay and organic matter, Hobart Butte Quarry, Oregon. ×90.

b—Kaolinite pellets (K) surrounded by clay and organic material in a fire clay of the Pennsylvanian period. Fulton, Missouri. ×90.

c—White kaolinite fragments (K) with clay containing organic matter and appreciable iron filling cracks (C). Pellet shaped fragments have resulted from the breaking up of larger chips. Some fragments show evidence of molding around fragments to fit the space available. Hobart Butte Quarry, Oregon. ×90.

d—Kaolinite pellets (K) surrounded by clay and organic matter, Castle Rock, Washington. ×90.

took place on the Eocene flood plains of the Hobart Butte area, and furnished at the source many separated fragments of the required sizes and shapes to produce a clay-pellet conglomerate when they were deposited.

The flattened shape of the pellets may have been inherited from the clay flakes or may be due to the weight of the overlying sediments. The fact that almost all of the pellets are parallel to the bedding suggests that some pressure was involved. If the flattening were entirely inherited from the original flakes one would expect that a few of the pellets would be deposited edgewise. The range in the ratio of the long to the short axes of the pellets also suggests that pressure was effective in flattening the pellets. Pressure increased with the weight of the accumulating sediments, and rapid deposition permitted the molding of the pellets while they remained somewhat plastic.

While the molding of pellets affords ample evidence of their deposition as a clay with some plasticity, the question

might well be asked if the clay had the composition of kaolinite when it was deposited or whether it was composed of another clay mineral which was later changed to kaolinite. On the southwest side of Hobart Butte about 200 feet below the summit kaolinite occurs as books in a leaf-bearing shale. This is the characteristic habit of kaolinite and suggests that a supply of kaolinite was available in the region during the deposition of the Calapooya formation. Fragments of pumice and welded tuffs now white kaolinite retaining original structures are enclosed in a red or purple iron-stained kaolinitic matrix at various levels throughout the Hobart Butte area. The alteration of volcanic glass to kaolinite must have been completed at the time of deposition because the alteration of the fragments to kaolinite could not have taken place after their deposition without bleaching ferric iron from the surrounding matrix. Finally, the lack of remnants of another clay mineral besides kaolinite in the pellets completes the reasons for concluding that the pellets had the composition of kaolinite when they were deposited.

The pellets containing lithic fragments may have been formed by the accretion of clay around these fragments or by having the lithic fragments included in the original clay flakes. Pellets within pellets may also have been formed by either of these mechanisms. That accretion was not the dominant process is suggested by: 1, the angularity of many of the pellets; 2, the lack of concentric layers; 3, the presence of white pellets surrounded by a red matrix; 4, the erosion of small pellets at the borders of large pellets; and 5, the presence of clay pellets in angular mud flakes. However, the one pellet that has a concentric structure may have grown by accretion.

Somewhat similar high-alumina clay-pellet rocks of sedimentary origin are found at widely separated localities—for example, in the Pennsylvanian rocks of the Eastern Coal fields, the Cretaceous and Eocene rocks of the Atlantic and Gulf Coasts, and the Cretaceous rocks of Colorado. At Castle Rock, Washington, they are interbedded in rocks of about the same age as those at Hobart Butte and in an area where there has been no hydrothermal activity. This fact, together with the fine-grained texture and kaolinitic composition of the pellets and matrix plus the lack of remnants of another clay mineral and the somewhat plastic condition of the pellets at the time of formation, indicates that the high-alumina content was original. This in turn suggests that a weathering profile was formed in this part of the Pacific Northwest, possibly sometime in the Eocene, that kaolinite was formed in the profile, and that it was concentrated into thin beds by selective erosion and deposition. This profile, like the source material of the widespread underclays of the Pennsylvanian series in Eastern North America, has not as yet been located with certainty. However, the presence of white pellets in a red matrix implies that the profile furnishing the Hobart Butte clays was in part high in iron and thus red and in part low in iron and probably nearly white.

SIGNIFICANCE

The initial kaolinitic composition of the pellets indicates that the matrix containing some plant materials or red iron oxides was also kaolinitic when it was deposited. The widespread distribution of these rocks testifies to the sedimentary origin of much of the clay on Hobart Butte. Later hydrothermal solutions altered non-kaolinitic to kaolinitic rocks thus increasing the tonnage of high-alumina material.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 15, NO. 1, P. 34

ANNOUNCEMENT

AEROGEOLOGY IN MINERAL EXPLORATION

Publication of Volume 39, Number 4, of the *Quarterly* of the Colorado School of Mines, Golden, Colorado has been announced by the Department of Publications. This, the October 1944 issue of the *Quarterly* contains "Aerogeology in Mineral Exploration" by W. S. Levings of the department of geology at the School of Mines.

This publication comprises 77 pages plus ten halftone inserts, nine double-page size, and includes a comprehensive bibliography. The primary purpose of the paper is to emphasize the possibilities of geological observations from the air, with special reference to aerial photographs taken from moderately great heights, as a powerful accessory to the modern equipment of the scientific explorer for mineral deposits.

Of secondary importance is the assembly in unit form of significant information concerning the results and techniques of aerial exploration, which, as a consequence of its being scattered in either relatively inaccessible publications or company files, has not been generally available to most interested persons.

Copies of this number of the *Quarterly* may be obtained from the Department of Publications, Colorado School of Mines, Golden, Colorado, at $1.00 postpaid.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 15, NO. 1, PP. 35–36

REVIEWS

R. A. BAGNOLD. *The Physics of Blown Sand and Desert Dunes, 1941*, London, pp. i–xx, 1–265.

This book presents a study of the behavior of sands in a wind tunnel with a controlled air stream and applications of the data acquired from such study to the formation of wind ripples and ridges and dunes. The author states that research into sand-dune formation should be divided into two stages of which one should consist of laboratory work with a suitable wind tunnel whereby some insight may be acquired into the physics of movement of sand grains in air streams and the reactions of the sand grains on the air streams, and a second stage in which would be investigated "the movement of an air stream over and round the curved surfaces of the accumulations which would then be taken as having risen out of the flat surface into the third dimension." Studies of the second stage are not presented. The studies required application of mathematical treatment of data acquired and this may discourage many readers.

The book consists of three parts in the first of which are presented "The Physics of Grain Movement" in eight chapters with titles as follows: Sand and Dust, The Behavior of Sand Grains in Air, Wind-Tunnel Observations, The Surface Wind, The Effect of Sand Movement on the Surface Wind, Confirmatory Measurements in the Desert, Threshold Wind Speed and the Size of Sand Grain, and Summary of the Physics of Grain Movement.

Part two considers in three chapters small scale effects, grain size distribution and wind ripples and ridges with titles of Grading Diagrams, Grading Changes in Non-uniform Sand, and Surface Ripples and Ridges.

Part three treats of large scale effects. This is done in six chapters of which the titles are Conditions for the Growth of a Sand Surface, Sand Shadows and Sand Drifts, The Barchan Dune, The Longitudinal or Seif Dune and the Whaleback, The Internal Structure of Sand Deposits, and Singing Sands.

There are 16 plates of which a few illustrate apparatus but most apply to features observed in the field. There are 83 text figures.

This book is well worth careful study by those interested in the movement of sand grains in air and the formation of features due to the movement. So far as the reviewer is concerned it is the first careful detailed study of the movement and accumulation of sand grains. The reviewer also considers the book to present the best explanations of the origin of wind ripples and ridges, and the barchan and seif (longitudinal) dunes.

All sedimentationists interested in the formation of wind ripple marks and dunes should read this book. The reading is not easy and the reviewer recalls having to read a sentence a half dozen times.

W. H. TWENHOFEL
University of Wisconsin

C. S. PIPER. *Soil and Plant Analysis, 1944*, pp. i-xiv, 1–368. Interscience Publishers, Inc. New York.

This book is what its title indicates and what its author states, "A Laboratory Manual of Methods for Examination of Soils and the Determination of the Inorganic Constituents of Plants." In the part on soil analysis there are considered methods of collection and preparation of soil samples; determination of hydrogen ion tension; mechanical analysis of soils; determination of single value soil constants as water holding capacity, moisture equivalent, etc.; soil color; standard solutions and indicators; base exchange; determination of calcium carbonate, nitrogen, organic matter, and free ferric oxide; and separation and analysis of the clay fraction. This part of the book covers three chapters.

Determination of the inorganic constituents of plants is treated in four chapters. There are considered the collection and preparation of plant samples; methods of ashing the plant materials; determinations of the more common inorganic constituents as silica, calcium, magnesium, potassium, sodium, phosphorus, chlorine, and sulphur; and of the trace elements of boron, cobalt, copper, iron, manganese, molybdenum, and zinc.

Many of the methods described are well known to students of sediments, but the book should be of considerable service in laboratory studies of sediments. Sedimentationists may well afford to own the book. The price ($4.50) seems reasonable.

W. H. TWENHOFEL

University of Wisconsin

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NOTE: The above Association and Society officers on the cover of Volume 14, Number 2, August 1944 were transposed in error by the printer.

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN